Which fine-tuning arguments are fine?

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Abstract

The argument from naturalness is widely employed in contemporary quantum field theory. Essentially a formalized aesthetic criterion, it received a meaning in the debate on the Higgs mechanism, which goes beyond aesthetics. We follow the history of technical definitions of fine tuning at the scale of electroweak symmetry breaking. It is argued that they give rise to a special interpretation of probability, which we call Gedankenfrequency. By extension of its original meaning, the argument from naturalness is used to compare different models beyond the Standard Model. We show that in this case naturalness cannot be defined objectively. Rather, it functions as socio-historical heuristics in particle physics and it contributes to the advent of a probabilistic version of Popper's falsificationism.

1 Introduction

Arguments from naturalness play an important role in particle physics of the last 25 years. Gerard 't Hooft was the first to introduce naturalness in this physical discipline, connecting it with symmetry:

> The naturalness criterion states that one such [dimensionless and measured in units of the cut-off] parameter is allowed to be much smaller than unity only if setting it to zero increases the symmetry of the theory. If this does not happen, the theory is unnatural. [59]

Emphasized in this definition, the connection of naturalness with symmetry could have provided a philosophical background for the former based on the conceptual importance of the latter. Concerning symmetry, since Plato and the 17th-century French debate between Claude Perrault and François Blondel, two opposing views have taken it to be, respectively, an expression of the aesthetic imperative of beauty and a human-invented instrument for better executing the job of the engineer. In turn, naturalness has both a connection with beauty and a heuristic, road-mapping role in science. Based upon 't Hooft's definition, it could have received a double conceptual foundation similar to that of symmetry. But history has chosen a more intriguing path. The original 't Hooft's idea faded away behind the many facets of the actual use of naturalness in particle physics.

Since the 1970s, the notion of naturalness has been gradually evolving away from the connection with symmetry. In what physicists say about its meaning

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one finds rare heuristic arguments as well as abundant references to beauty: naturalness is an "aesthetic criterion" [5], a "question of aesthetics" [30], an "aesthetic choice" [7]. Sometimes the aesthetical significance of naturalness and the heuristic role are mixed together: "the sense of 'aesthetic beauty' is a powerful guiding principle for physicists" [36].

One must not belittle the place of beauty in the scientist's thinking. An intuitive aesthetic sense can be developed by the practice of mathematical reasoning and it can then serve as a thinking aid. In mathematics, once beauty and elegance have shown the way to new discoveries, all the results must be rigorously established through proof. In natural science, "rational beauty" [50] can only be admired at the end of inquiry, when we have established a sound scientific account in agreement with nature. Einstein vividly supported this view early in his life, saying that aesthetically motivated arguments "may be valuable when an *already found* [his emphasis] truth needs to be formulated in a final form, but fail almost always as heuristic aids" [32]. Used as a guide for discovering reality, aesthetic arguments may indeed turn out to be extraordinarily fruitful as well as completely misleading, and so for two reasons.

First, because the real universe is not just beautiful: one can also discern in it futility [61] or inefficiency [31]. Nature is not what the American physicist Karl Darrow thought she was, when he stated that it would be more "elegant" if there were only two particles in the atomic nucleus [26]. Perhaps the most outspoken promoter of mathematical beauty in physics, Dirac has many times been led by it into scientifically sterile byways [41, chapter 14]. Thus beauty is not an exclusive characteristic of the results of science and should not be elevated to a research imperative.

Second, because there is no necessary link between beauty and empirically verified truth. The two notions are disconnected: the beautiful may be false, and the true may be ugly. In spite of a long debate on this topic between eminent physicists (e.g., see [22]), we maintain that beauty and truth, as well as beauty and good, are distinct categories, in physics in particular. Aesthetic arguments are a methodologically problematic and a potentially misleading lighthouse on the road to sound science in the physical universe.

In Section 2, we review physics of the Higgs mechanism and remind that the argument from naturalness often gives the impression of being a perfectly normal scientific argument. Section 3 describes the many lines of development of the concept of naturalness in particle physics. Among all fine-tuning arguments, the valid one is neither anthropic (Section 4) nor an argument from beauty. We argue in Section 5 that it involves a special interpretation of probability and is meaningful only if naturalness in particle physics is understood as heuristics. Practicality of being guided by the considerations of fine tuning then stems not as much from aesthetics as from the down-to-earth sociological factors, which determine the physical theory's way of development. Naturalness can be best warranted with the help of historical analysis.

2 The Higgs mechanism

The observed weak interaction is not locally gauge invariant and its unification with electromagnetism must take it into account. To this end, a mechanism must be introduced within any unified theory of electroweak (EW) interactions to put the two interactions back on unequal grounds. By offering one such mechanism the Standard Model (SM) describes electroweak symmetry breaking quantitatively. Invented in 1964 independently by several different groups, this so-called Higgs mechanism builds on the fact that a massless spin-one particle has two polarization states and a massive one has three. Electroweak symmetry breaking produces a would-be Goldstone boson, whose physical degree of freedom is absorbed by the massless gauge boson. Number of polarization states of the latter then increases from two to three and it becomes massive. Such massive gauge bosons account for the absence of gauge symmetry in the observed weak interaction.

This description was quickly recognized to be not very compelling due to its lack of explanatory power [36, 53]. Many physicists did not find important the conceptual problems of the Higgs mechanism simply because they took it for no more than a convenient, but temporary, solution of the problem of electroweak symmetry breaking. Jean Iliopoulos said at the 1979 Einstein Symposium: "Several people believe, and I share this view, that the Higgs scheme is a convenient parametrization of our ignorance concerning the dynamics of spontaneous symmetry breaking, and elementary scalar particles do not exist" [40]. But, with time, things have changed. Discovery of W and Z bosons and a growing amount of electroweak precision data confirmed the ideas of Weinberg and Salam. Not only is there today confidence in the Standard Model, but it is clear that changing it ought to be exceptionally difficult, due to an exceedingly large number of tests with which any model beyond the Standard Model (BSM) must conform. By 2004, Ed Wilson was completely assured: "A claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies ... makes no sense" [64].

The SM Higgs mechanism is a pleasingly economical solution for breaking the electroweak symmetry. However, the global fit of the electroweak precision data is consistent with the Standard Model only in case one takes an average over all available experimental data: then arises the usual prediction of a relatively light Higgs $m_H < 182$ GeV [39]. Troubles occur, when one looks at the details of the data: different ways of calculating the Higgs mass m_H, based on distinct experimental measurements, lead to incompatible predictions. Overlap between EW precision tests is less than 2% (Figure 1).

For example, the value of the top quark mass extracted from EW data (excluding direct Tevatron measurements) is $m_t = 178.9^{+11.7}_{-8.6}$ GeV, while the CDF/D0 result is $m_t = 172.6 \pm 0.8(\text{stat}) \pm 1.1(\text{syst})$ GeV [35]. This discrepancy worsens considerably the SM fit. Of more direct impact on the light Higgs hypothesis is the observation that two most precise measurements of the Weinberg angle $\sin^2 \theta_W$ do not agree very well, differing by more than 3σ. The $b\bar{b}$ forward-backward asymmetry $A^{0,l}_{fb}$ measured at LEP gives a large value of $\sin^2 \theta_W$, which
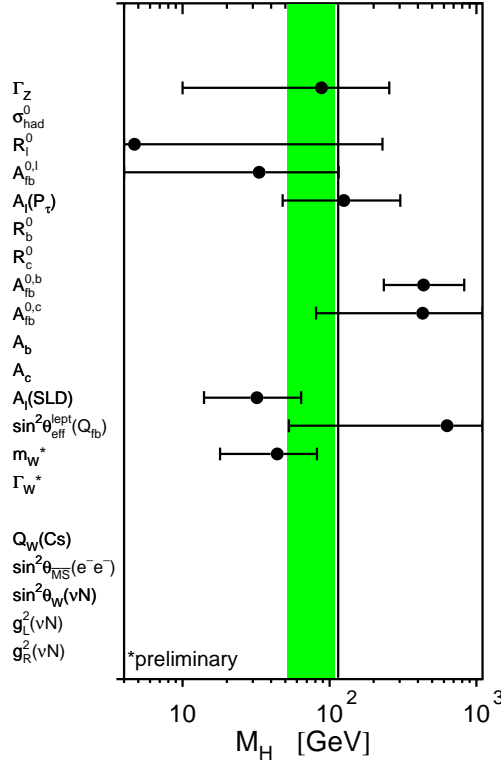
Figure 1: Values of the Higgs mass extracted from different EW observables. The vertical line is the direct LEP lower limit of 114 GeV. The average is shown as a green band [39].

leads to the prediction of a relatively heavy Higgs with $m_H = 420^{+420}_{-190}$ GeV. On the other hand, the lepton left-right asymmetry A_l measured at SLD (in agreement with the leptonic asymmetries measured at LEP) gives a low value of $\sin^2 \theta_W$, corresponding to $m_H = 31^{+33}_{-19}$ GeV, in conflict with the lower limit $m_H > 114$ GeV from direct LEP searches [9]. Moreover, the world average of the W mass, $m_W = 80.392 \pm 0.029$ GeV, is larger than the value extracted from a SM fit, again requiring m_H to be smaller than what is allowed by the LEP Higgs searches [37].

For a physicist, inconsistency between the predictions of the Higgs mass means that the argument in favor of the SM with a light Higgs is "less compelling" [37]. What message exactly is encoded in the 2% overlap? Does this number correspond to some probability? In what sense does the smallness of this value make the SM Higgs less compelling?

3 Measures of naturalness

3.1 Hierarchy problems

The Standard Model suffers from a 'big' hierarchy problem: in the Lagrangian, the Higgs mass parameter m_H^2, which is related to the physical mass by $m_h^2 = -2m_H^2$, is affected by incalculable cut-off dependent quantum corrections. Whichever new theory, possibly including gravitation, replaces the Standard Model above some energy scale $\Lambda_{\rm NP}$, one can expect the Higgs mass parameter to be of the same size as (or bigger than) the SM contribution computed with a cut-off scale $\Lambda_{\rm NP}$. This way of estimating the size of the Higgs mass is made reasonable by the analogy with the electromagnetic contribution to $m_{\pi^+}^2 - m_{\pi^0}^2$. The leading quantum correction is then expected to come from the top quark sector and is estimated to be [53]

$$\delta m_H^2 \sim -\frac{3\lambda_t^2}{8\pi^2}\Lambda_{\rm NP}^2 \,. \tag{1}$$

This contribution is compatible with the allowed range of m_h^2 only if the cut-off is rather low

$$\Lambda_{\rm NP} < 600 \times (\frac{m_h}{200\,{\rm GeV}})\,{\rm GeV} \,. \tag{2}$$

Now, if the energy range of the SM validity is as low as 500 GeV – 1 TeV, why did previous experiments not detect any deviation from the SM predictions? Even though the center of mass energy of these experiments was significantly lower than 1 TeV, still their precision was high enough to make them sensitive to virtual effects associated with a much higher scale.

To state it in other terms, note that effects from new physics at a scale $\Lambda_{\rm NP}$ can in general be parametrized by adding to the SM renormalizable Lagrangian a tower of higher dimensional local operators, with coefficients suppressed by suitable powers of $\Lambda_{\rm NP}$:

$$\mathcal{L}_{eff}^{\rm NP} = \frac{1}{\Lambda_{NP}^2}\left\{c_1(\bar{e}\gamma_\mu e)^2 + c_2 W_{\mu\nu}^I B^{\mu\nu}H^\dagger\tau_I H + \ldots\right\} \,. \tag{3}$$

At the leading order it is sufficient to consider only the operators of lowest dimension, $d = 6$. The lower bound on $\Lambda_{\rm NP}$ for each individual operator $\mathcal{O}_i$, neglecting the effects of all the others and normalizing $|c_i| = 1$, ranges between 2 and 10 TeV. Turning several coefficients on at the same time does not qualitatively change the result, unless parameters are tuned [53]. The interpretation of these results is that if new physics beyond the SM affects electroweak observables at the tree level, in which case $c_i \sim O(1)$, then the generic lower bound on its threshold Λ_{NP} is a few TeV. The tension between this lower bound and eq. (2) defines what is known as the 'little' hierarchy problem.

The little hierarchy problem is apparently mild. But its behaviour with respect to fine tuning is problematic. If fine tuning of order ϵ is tolerated, then the bound in eq. (2) is relaxed by a factor $1/\sqrt{\epsilon}$. The needed value of ϵ grows quadratically with $\Lambda_{\rm NP}$, so that for $\Lambda_{\rm NP} = 6$ TeV one needs to tune to 1 part in

a hundred in order to have $m_H = 200$ GeV. The goal of this section is to make a precise statement about the meaning of this fine-tuning problem.

3.2 Standard definition

The first modern meaning of naturalness is a reformulation of the hierarchy problem. It arises from the fact that masses of scalar particles are not protected against quantum corrections, and keeping a hierarchical separation between the scale of EW symmetry breaking and the Planck scale requires the existence of a mechanism that would 'naturally' explain this hierarchy. Although the difference in scales is a dimensionless parameter much smaller than unity ($\frac{10^3 \text{GeV}}{10^{19} \text{GeV}} = 10^{-16}$), setting it to zero in accordance with 't Hooft's prescription is out of question because gravity exists even if it is weak*. With all its known problems, the Standard Model does not become more symmetric in the hypothetical case where gravity is infinitely weaker than the weak interaction. Therefore, 't Hooft's criterion does not apply and naturalness needs a new definition.

According to Wilson [57], naturalness means that the observable properties of a system should be stable against minute variations of the fundamental parameters. This 1978 formulation corresponds exactly to the lesson contained in the hierarchy problem. It came at the end of a decade filled with debates on the instability of the Higgs mass. In an article written at the end of 1970, Wilson had clearly stated his doubt that the Higgs mechanism could be fundamental: "It is interesting to note that there are no weakly coupled scalar particles in nature; scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry. ... Mass or symmetry-breaking terms must be 'protected' from large corrections at large momenta due to various interactions (electromagnetic, weak, or strong). ... This requirement means that weak interactions cannot be mediated by scalar particles" [63]. After ten years of such and similar doubts in the electroweak symmetry breaking through the Higgs mechanism, the Standard Model was experimentally verified, and little room remained for challenging its constitutive theoretical components. If the hierarchy problem were to be tackled, the Standard Model now had to be complemented rather than discarded.

In the years around 1980, supersymmetry advanced on the foreground as a plausible extension of the problematic physics of electroweak symmetry breaking in the Standard Model. Consequently, naturalness began to be discussed in the context of supersymmetric models with their enlarged content of particles and the new predicted phenomena, e.g., in a seminal paper by Witten [65]. As the number of proposed supersymmetric extensions of the Standard Model increased, a formalization of naturalness was needed to evaluate their effectiveness in solving the big hierarchy problem. The first such measure was defined in mid-1980s as a quantitative analogue of Wilson's formulation.

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*One exception from this argument are models with large extra dimensions, where the scale of gravity is different from 10^{19} GeV [6].

Barbieri and Giudice looked at various realizations of low-energy supersymmetric phenomenology arising from supergravitational models [10, 34]. They interpreted the notion of naturalness by equating it with the sensitivity of the electroweak symmetry breaking scale (instantiated as the Z-boson mass m_Z) with respect to variations in model parameters. For a general observable O depending on parameters p_i at point P' this sensitivity is:

$$\Delta_{BG}(O; p_i) = \left| \frac{p_i}{O(p_i)} \frac{\partial O(p_i)}{\partial p_i} \right|. \tag{4}$$

Barbieri and Giudice then chose number 10 as a *natural* upper bound on Δ_{BG}. The motivation was their subjective belief that if the discrepancies between quantities were to be natural, they must be less than of one order of magnitude. Yet, as such, the choice of a number is arbitrary. In a different context (discussing naturalness in semantic chains), Lewis shows that the establishment of an endpoint of perfect naturalness is connected with our own appreciation of what is "not too complicated" [43, p. 61]. The opinion in such matters apparently can evolve: ten years after the Barbieri-Giudice definition, when the experimental constraints on the leading BSM candidate — minimal supersymmetric standard model (MSSM) — became stronger, one had to require a fine tuning of 20 for the model survival [23, 11]. Double the value of the old endpoint, this new limit of naturalness also became accepted as "reasonable" [21].

Note that eq. (4) only involves infinitesimal variations in p_i. It follows that the Barbieri-Giudice definition gives a measure of naturalness of a given model considered on its own, independently of the rival models which differ in the values of parameters but also pretend to solve the big hierarchy problem. This definition has been used widely and has helped to sort out the claims of different supersymmetric models about how well they succeed in removing the big hierarchy problem of the Standard Model. But it also failed to address a new set of issues in the flourishing enterprise of model building.

3.3   Naturalness in supersymmetric models

In the late 1980s, BSM models began to be studied more thoroughly and a multitude of their consequences became apparent, often unconnected with the big hierarchy problem. Comparing this predicted phenomenology with the growing ensemble of experimental data from particle accelerators required a new notion of fine tuning. Now naturalness must have encompassed many observables (and not just the Z mass). As a side effect of this evolution, the definitions of naturalness no more considered only infinitesimal changes in parameters, but a finite range of their values.

In spite of supersymmetry not being the only available solution of the big hierarchy problem, a long line of studies have used fine tuning to make guesses about the masses of sparticles. Early on, the MSSM parameter space was scrutinized, later leaving the place to that of NMSSM. In an article belonging to this current, de Carlos and Casas [27], who were critically reviewing an earlier work which used the Barbieri-Giudice measure [54], realized that a measure of

sensitivity need not always be a measure of fine tuning. But they only concluded that one should take 20 rather than 10 as a numerical limit of natural Δ_{BG}.

More radically, a newly defined measure appeared in 1994, when Anderson and Castaño refined the Barbieri-Giudice definition in order to exclude such situations, i.e., when sensitivity is present in a model for other reasons than fine tuning [3]. They divide the Barbieri-Giudice measure by its average value $\bar{\Delta}$ over some "sensible" range of parameters p_i:

$$\Delta_{AC} = \frac{\Delta_{BG}}{\bar{\Delta}_{BG}} \tag{5}$$

This range can be specified by *fiat* or can be chosen so as to encompass all parameter values at which the model's experimentally valid predictions remain unperturbed. Naturalness then can be defined, in a slight modification of Wilson's language, as a condition that observable properties of a system be "not unusually unstable" against minute variations of the fundamental parameters. The new word "unusual" implies comparison with the introduced range of parameters and has a first-order conceptual importance. Indeed, historically it has brought the meaning of the fine-tuning argument in particle physics closer to probabilistic estimates based on the anthropic reasoning.

That a range of parameters is involved in the definition of naturalness means that parameter values in a particular model begin to be seen as just one instantiation on the broader distribution of *possible* parameters. Anderson and Castaño became the first to connect naturalness to the "likelihood" of a given set of Lagrangian parameters. They presupposed that there exist a way in which "we parametrize our assumptions about the likelihood distribution of the theory's fundamental parameters" [4]. The range over which vary parameters p_i then arises as a mathematical representation of such assumptions. Anderson and Castaño were so led to consider a class of identical models only differing in the values of fundamental parameters, i.e., what we call today a landscape of scenarii defined by the values of p_i. Distribution of parameters over their allowed range was uniform and all values were considered equally likely.

If Anderson and Castaño were careful to speak about naturalness only as likelihood of certain parameters, very soon did the word 'probability' enter the stage. Introduced by Strumia and his co-authors, probability was not yet the probability of a particular scenario seen on a landscape of many, but a mere inverse of the Barbieri-Giudice measure of fine tuning. The latter was now "supposed to measure, although in a rough way, the inverse probability of an unnatural cancellation to occur" [11]:

$$P \sim \Delta_{BG}^{-1}. \tag{6}$$

In a paper discussing naturalness of the MSSM, Ciafalano and Strumia speak about probability as a "chance to obtain accidental cancellations" in M_Z [25]. They attempt to demonstrate that the choice of a particular limiting value of Δ_{BG} is no more then a choice of a "confidence limit on unprobable [sic] calculations". This is how probability as a degree of confidence, i.e., in the Bayesian

sense, made its way into particle physics. Strumia goes on to suggest that probability could be normalized by requiring that it be equal to 1 in the situations where "we see nothing unnatural". What this phrase means precisely is left to our subjectivity. However, the normalization problem is very important: its difficulty lies with the fact that most attempts to rigorously define parameter space lead to non-normalizable solutions, so that it is impossible to define the ratios between regions of these spaces [44]. Thus Strumia's use of 'probability' is metaphoric. This probably was the reason why, previously, Anderson and Castaño had avoided this term and had only spoken about 'likelihood'.

The originally metaphoric phrase "roughly speaking, Δ_{BG}^{-1} measures the probability of a cancellation" proved popular (see, e.g., [18]). It was used by Giusti *et al.*, when they variously spoke about "naturalness probability" or "naturalness distribution probability" [38]. This line of thought refers to probability because it needs a justification for doing a Monte Carlo calculation of "how frequently numerical accidents can make the Z boson sufficiently lighter than the unobserved supersymmetric particles". It is remarkable that, although Bayesian in its roots (Monte Carlo being a Bayesian method), probability is seen here as the frequency of an event occurring only in the thought experiments, performed by an agent who imagines worlds with different values of the parameters of supersymmetry. This *Gedankenfrequenz* interpretation of probability becomes typical for a group of papers on fine tuning in supersymmetric models. Although frequentist in its formulation, it is a variant of the Bayesian point of view because it relies on the subjective assignment of priors, which corresponds to Anderson's and Castaño's "way in which we parametrize our assumptions". Initially the agent's freedom to give a value to the prior probability is limited by the boundaries of the allowed region of parameter space. Once in the allowed region, stategies vary. On the one hand, Giusti *et al.* propose to choose values randomly and use them in a calculation which leads to assigning a Bayesian level of confidence to the sets of parameters. On the other hand, among many articles using the Markov Chain Monte Carlo (MCMC) procedure for MSSM, one finds other choices of priors, such as "naturalness-favouring prior" [2] or "theoretical probability of a state of nature" [15].

Resulting in what they called 'LHC forecasts', these Bayesian studies make "though reasonable, rather arbitrary" predictions about future experiments. It is important that this approach has paved the way to understanding Strumia's metaphoric probability in the statistical sense. When ten years later Casas *et al.* will be comparing definition (10) with definition (9), they will speak about "the statistical meaning" of fine tuning [20].

3.4 Naturalness in model comparison

Defining naturalness with the help of a finite range of parameters corresponding to different model-building scenarii became a dominant trend. Particle physics was now seen as consisting of scenarii [7, 19, 20]. Naturalness was redefined in this new language: it became a measure of "how atypical" are certain physical scenarii [7]. If the use of fine tuning had previously been limited to emphasizing

the problems of a particular model, many physicists state after the year 2000 that naturalness is used to compare models.

Anderson and Castaño modified the Barbieri-Giudice measure, eq. (5) instead of eq. (4), because of the problem of global sensitivity. Athron and Miller went further to consider models with several tuned observables as well as finite variations of parameters [7]. Parameters themselves are no more required to be uniformly distributed over the considered range of parameter space. To give a quantifiable version of this larger notion, Athron and Miller speak about "generic" scenarii and "typical" volumes of parameter space formed by "similar" scenarii. Introduced in the first modifications of the Barbieri-Giudice measure as a finite range of parameters, exploration of the larger parameter space far from the point P' reaches here its apogee.

To define 'similar' and 'typical', Athron and Miller claim in opposition to Anderson and Castaño that the definitions must be "chosen to fit to the type of problem one is considering". They argue that a typical volume of parameter space cannot be the Anderson-Castaño average of volumes G throughout the whole parameter space, $\langle G \rangle$, for it would depend only on how far the parameters are from some "hypothesized upper limits on their values". For example, an observable O which depends on a parameter p according to $O = \alpha p$, will display fine tuning for small values of p if one chooses the maximum possible value of p to be large. In the Anderson-Castaño approach, upper limits on parameters arise from the requirement that the model's meaningful predictions be preserved. For Athron and Miller this is too generic.

To fit the choice to particular cases, they introduce similar scenarii defined by a "sensible" choice of how far numerically the observable value may deviate from a given one. Let F be the volume of dimensionless variations in the parameters over some arbitrary range $[a, b]$ around point P' and G be the volume in which dimensionless variations of the observable fall into the same range:

$$a \leq \frac{p_i\left(P\right)}{p_i\left(P'\right)} \leq b, \quad a \leq \frac{O_j\left(\{p_i\left(P\right)\}\right)}{O_j\left(\{p_i\left(P'\right)\}\right)} \leq b. \tag{7}$$

In their MSSM calculation Athron and Miller use $a = b = 0.1$ claiming that this 10% threshold amounts to not encountering a "dramatically different" physics. The measure of fine tuning then is

$$\Delta_{AM} = \frac{F}{G}. \tag{8}$$

This measure can be applied straightforwardly in the case of a single observable like the Z mass, but it can also be applied to compare the tuning between different observables. In the latter case F and G are volumes in the multi-dimensional spaces of, respectively, parameters and observables. The former space is not new, for the notion of naturalness defined by many parameters dates back to Barbieri and Giudice:

$$\Delta = \max_i \{\Delta_{BG}(p_i)\}. \tag{9}$$

Alternative variants have also been proposed, such as [17, 19]

$$\Delta = \sqrt{\sum_i \Delta_{BG}\left(p_i\right)}. \tag{10}$$

On the contrary, introducing a multi-dimensional space of observables is a novelty.

With the development of model building it became clear that the big hierarchy problem was not the only fine tuning to be found. Many experimental parameters were measured constraining the values of parameters in BSM models, such as quark masses, the strong coupling constant, the anomalous magnetic moment of the muon, the relic density of thermal dark matter, smallness of flavor violation, non-observation of sparticles below certain thresholds and so forth. Fine tunings produced by these measurements are "morally similar" [55] to the fine tuning from m_Z. A variety of heuristics are then possible. One can consider the most constraining fine tuning or some form of the average of many tunings. Motivations from different tunings may not be equally "compelling" and less remarkable parameters may be therefore discarded.

Still the Anderson-Castaño problem of upper limits on p cannot be avoided even if one defines similar scenarii independently. Athron and Miller wish to maintain decorrelated tunings and to vary each observable without regard for others. Individual contributions to volume G are then made with no concern for contributions from other observables. At this point Athron and Miller realize that observables can only be compared if Δ_{AM} is normalized. To do so, they are forced to reintroduce the Anderson-Castaño average value (5):

$$\hat{\Delta}_{AM} = \frac{1}{\Delta}\frac{F}{G}, \tag{11}$$

which relies on the knowledge of the total allowed range of parameters in a particular model. The hypothesized upper limit of this range determines how compelling the naturalness argument for new physics will be. The same normalization procedure is essential if one wants to use fine tuning to compare different models.

Although it appears in the literature as an incremental refinement of the original Wilson's idea through the work of Barbieri, Giudice, Anderson, Castaño and others, the Athron-Miller notion of naturalness lies very far from Wilson's. Naturalness has become a statistical measure of how atypical is a particular scenario. It is now tempting to use the numerical value of fine tuning to set off several scenarii against each other: the least tuned scenario is to be preferred, where 'preferred' is understood in a practical, heuristic sense of model building. In practice, not only similar (in the Athron-Miller sense) scenarii are compared according to the value of their fine tuning, but models predicting completely different physics are sometimes brought into a competition against each other on the basis of their naturalness. On the one hand, one reads that:

The focus point region of mSUGRA model is *especially compelling*

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in that heavy scalar masses can co-exist with low fine-tuning... [8, our emphasis]

We ...find *preferable* ratios which reduce the degree of fine tuning. [1, our emphasis]

On the other hand, such claims are mixed with assertions going beyond the applicability of the Anderson-Castaño or even the Athron-Miller definitions:

Some existing models... are not *elevated* to the *position* of supersymmetric standard models by the community. That may be because they involve fine-tunings... [14, our emphasis]

In order to be *competitive* with supersymmetry, Little Higgs models should not worsen the MSSM performance [in terms of the degree of fine tuning]. Fine tuning much higher than the one associated to the Little Hierarchy problem of the SM ...or than that of supersymmetric models ...is a serious drawback. [19, our emphasis]

...the fine-tuning *price* of LEP... [23, 11, our emphasis]

Comparing altogether different models by confronting the numbers, e.g., being tuned at 1% against being tuned at 10%, is meaningless unless one of two conditions is met: either the two models can be put in the common parameter space and the Athron-Miller definition is to be used, or conclusions drawn from such comparison are employed in a particular way. Because they cannot be said to bear on truth value of the models, they can be understood as shaping the historic and sociological competition between otherwise uncommensurable models.

4   Ontological interpretation

4.1   The anthropic connection

The naturalness problem was one of the factors that gave rise to theories beyond the Standard Model. Since the 1970s, the SM began to be viewed as an approximation to some future fundamental theory, i.e., an effective field theory (EFT) valid up to some limit Λ_{NP}. The fundamental theory may involve gravity, and the SM would then become its low-energy limit. The EFT approach relies crucially on the assumption of decoupling between energy scales and the possibility to encode such a decoupling in a few modified constants of the field-theoretic perturbation series. This connects EFT with naturalness.

Understood as a hierarchy problem, naturalness is the measure of stability against higher-order corrections in the perturbation series. If the higher-order corrections were important, it would invalidate the use of the perturbation expansion and, together with it, the EFT method. "If the experiments at the LHC find no new phenomena linked to the TeV scale, the naturalness criterion would fail and the explanation of the hierarchy between electroweak and gravitational scales would be beyond the reach of effective field theories. But if new

particles at the TeV scale are indeed discovered, it will be a triumph for our understanding of physics in terms of symmetries and effective field theories" [36].

If low-energy models (e.g., MSSM) are EFTs with respect to some unified theory involving gravitation (e.g., supersymmetric models of gravity), it is possible to speak within one and the same theory about the fine tuning of low-energy observables (like m_Z) as well as about the fine tuning of the cosmological constant. Thus fine tuning in particle physics and fine tuning is cosmology become connected. While the latter tuning has a long tradition of been interpreted anthropically, it is through this connection that the former tuning acquires a tint of anthropic meaning.

Introduction of the range of parameter values in the definitions of naturalness, eqs. (5), (8), and (11), pushes one in the direction of the many-worlds ontology. If every value from the range of parameters is realized in some world, one can justify the fine tuning argument as a probability distribution corresponding to our chances to find ourselves in one of these ontologically real worlds. This interpretation seems totally fictitious, but it is the one shared intuitively by many physicists, particularly string theorists and cosmologists [16]. It inserts the fine-tuning argument in a larger class of anthropic arguments based on the many-worlds reasoning.

The argument goes as follows. 1°, establish that the descriptions of worlds with different values of parameters are mathematically consistent and not precluded by the theory. 2°, establish that such worlds really exist. For this, refer to Gell-Mann's "totalitarian principle", requiring that anything which is not prohibited be compulsory [13]. Alternatively, refer to what Dirac called "Eddington's principle of identification", that is, asserting the realist interpretation of mathematical quantities as physical entities [28]. Or extrapolate to all physics Peierls's position that "in quantum electrodynamics one has always succeeded with the principle that the effects, for which one does not obtain diverging results, also correspond to reality" [48]. 3°, establish that among all possible worlds those containing highly fine-tuned models are statistically rare, for their probability is defined by the inverse fine tuning. Indeed, the definition of "unnatural" was so chosen that, compared to the full number of worlds, the proportion of unnatural worlds is necessarily tiny. 4°, conclude that if we evaluate our chances to be in such a world, the resulting probability must be low.

This argument can, and has been, criticized at every step from 1 to 4. For example, depending on the concrete variety of the anthropic argument, the pronoun 'we' (step 4) refers either to intelligent beings, or worlds with carbon-based life, or else worlds with complex chemical elements and so forth. Logically, everything happens as if there were a choice-making meta-agent with access to reason. But with an ontological interpretation of worlds, this meta-agent becomes a super-agent with a power of action extending over the many worlds, who blindly decides to put us in a world of her choice. The existence of such super-agent is of course metaphysical. Yet it warrants the posture that, provided our task to predict in which world we shall end up, we cannot fare better than guess it probabilistically, by taking the inverse of the fine tuning measure Δ.

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The specific problem of the anthropic argument in particle physics, emphasized in Section 3, is that the 'full number of worlds' (step 3) can be only defined arbitrarily. Upper limits of the range of parameter values have to be set by *fiat*. If one goes in this too far, it would preclude some worlds from existing without a contradiction with theory or data, thus violating the requirement at step 1. But how far one can go in parameter variations and keep the premises of step 1 intact is not obvious. At the first sight, this difficulty may seem unremarkable and the anthropic argument would seem a valid implication. Inconspicuity of the limit problem, which is often left unmentioned, is similar to the general disregard among physicists of the frequent use of 'probability' in a metaphoric, formally indefensible sense. Yet if the story of naturalness in particle physics teaches a clear lesson about anthropic reasoning, it is about how to show its arbitrariness on a concrete example.

4.2   Counterfactuals

The fine-tuning argument shares with a larger class of anthropic arguments a twofold logical nature: these arguments can either be formulated in purely indicative terms or by using counterfactuals. The first kind of formulations, using only indicative terms, are typically employed by opponents of the anthropic principle [56]. They mean to dissolve the apparent explanatory power of the argument by rewording it in terms of facts and of the laws of inference in classic Boolean logic. Devoid of the counterfactual, the anthropic argument indeed becomes trivial.

The second kind of logic involving explicit counterfactuals is more common. Anthropic arguments take the form of statements such as 'If parameters were different then intelligent life would not have existed"; or 'If parameters were different then complex chemistry would not have existed'; or 'If parameters were different then carbon-based life would not be possible'. The principal question is to find out whether such statements are explanatory, and if yes, then in what sense. Answers to it typically involve a detailed analysis of the counterfactual semantics. We only note here that there exists a physical, but no less fundamental than any logical, problem of validity and applicability of a counterfactually formulated argument.

Counterfactuals in physics have been discussed at least since the Einstein, Podolsky and Rosen paper about quantum mechanics in 1935 [33]. The key point in the EPR argument is in the wording: "If. . . we had chosen another quantity. . . we should have obtained. . . ". The Kochen-Specker theorem and Specker's discussion of counterfactuals in 1960 placing them in the context of medieval scholastic philosophy were the starting point of a heated debate on the use of counterfactuals in quantum mechanics (for recent reviews see [60, 58]). Peres formulated perhaps clearest statements about the post-Bell-theorem status of counterfactuals:

> The discussion involves a comparison of the results of experiments
> which were actually performed, with those of hypothetical experi-

ments which could have been performed but were not. It is shown that it is *impossible to imagine* the latter results in a way compatible with (a) the results of the actually performed experiments, (b) long-range separability of results of individual measurements, and (c) quantum mechanics. ...

There are two possible attitudes in the face of these results. One is to say that it is illegitimate to speculate about unperformed experiments. In brief "Thou shalt not think." Physics is then free from many epistemological difficulties.... Alternatively, for those who cannot refrain from thinking, we can abandon the assumption that the results of measurements by *A* are independent of what is being done by *B*. ... Bell's theorem tells us that such a separation is impossible for individual experiments, although it still holds for averages. [49]

The debate in quantum mechanics shows that the applicability of Boolean logic to statements about physical observables should not taken for granted in any branch of physics, especially those based on quantum mechanics. Quantum field theory is one. Simply, its focus has stayed with technical feats for so long that conceptual issues about measurement, inherited from quantum mechanics, have been neglected. The tendency has prevailed to assign values to unobserved parameters in experimental settings which cannot be realized in principle, e.g. in the case of *Gedankenfrequenz*.

Admittedly, even if the counterfactual in the fine-tuning argument in particle physics bears on physical parameters in the worlds impossible to observe, this does not lead to a direct contradiction with quantum mechanical theorems, for quantum mechanics deals with normalized probability spaces and Hermitian observables. It nonetheless remains true that the logic of anthropic arguments runs counter to the trend warranted by the lessons from quantum mechanics. Speculation about unperformed experiments is illegitimate not only in the case of unrealized measurements of Hermitian operators, but in a more general sense: it is unsound to extend to unperformed experiments in unrealized worlds the Boolean logical structure allowing us to say that physical constants in those worlds have definite values.

This line of critique resonates with Bohr's answer to Professor Høffding when the latter asked him and Heisenberg during a discussion at the University of Copenhagen: "Where can the electron be said to be in its travel from the point of entry to the point of detection?" Bohr replied: "To be? What does it mean *to be*?" [62, p. 18-19] The fine-tuning argument in particle physics, as well as anthropic arguments involving the cosmological constant, employ counterfactuals that contain the verb 'to be' in the conditional. What it means that a world which is referred to in this conditional, *had been*, *was* or *is*, would have been unclear for Bohr. He was greatly concerned with the meaning of utterances, famously claiming that "physics is what we can say about physics" [62, p. 16]. In the case of fine tuning this claim may be understood as a radical warning to all those who interpret fine tuning ontologically.

5 Probabilistic falsification

5.1 Interpretation of probability

Casas *et al.* consider two tunings of two different observables and propose that "since Δ and $\Delta^{(\lambda)}$ represent independent inverse probabilities, they should be multiplied to estimate the total fine tuning $\Delta \cdot \Delta^{(\lambda)}$ in the model" [19]. This is clear evidence of the statistical meaning of naturalness, shared by many particle physicists since the work of Ciafaloni and Strumia [25]. We argued in Section 3.3 that the notion of probability must be interpreted here in a peculiar way combining a frequentist approach with Bayesianism. Frequency is *Gedankenfrequenz*, because one counts the number of particular occurrences in the class of imaginary untestable numerical scenarios, instantiated as points in the parameter space. The Bayesian component arises in the form of degree of confidence, for one is concerned with our current ignorance of the true value of a parameter, which we believe to be measured in the future. When a parameter has already been measured, even outspoken proponents of the statistical meaning of naturalness admit that "assigning to it a probability can be misleading" [19]. Therefore, the fine-tuning argument is to be understood as a bet on our future state of knowledge, and it loses all meaning at the moment of actual measurement. *Hic et nunc* the future state of knowledge does not exist, and the bet is subjective. However, in our mind it does exist, and in this mental reality naturalness can be interpreted as frequency.

Two conditions must be met for one to have the ability, by way of naturalness, of making bets on future physics. First, experimental data must lack dramatically, so that uncertainty be complete as for which model better describes reality. This is indeed the case in particle physics. Second, we must hold a belief that in the future, hopefully soon enough, this veil of uncertainty will be lifted. Moreover, we ought to take it for granted that the lifting of the veil will unambiguously determine which of our current models is right and which is wrong. Subjective bets make sense only if the future state is a choice between the available alternatives. Physicists using the fine tuning argument hold such a belief indeed. If they refer to naturalness, they assume full confidence that the true description of reality will be picked out of the current models, once and for all, at the LHC or later experiments.

As in the general case of probabilistic reasoning in a situation of uncertainty (see, e.g., [45]), the fine tuning argument is the last resort when no scientific explanation can be provided. Psychologically, it is very difficult to resist the temptation to make a "statistical guess" [19] at the future state of knowledge. Although naturalness provides guidance but adds nothing to scientific truth, accepting its irrelevance and "living with the existence of fine tuning" [30] is a hard way of life. This temptation though is not completely unfamiliar as we already live in a world with many fine tunings, for example:

- The apparent angular size of the Moon is the same as the angular size of the Sun within 2.5%.

- The recount of the US presidential election results in Florida in 2000 had the official result of 2913321 Republican vs. 2913144 Democratic votes, with the ratio equal to 1.000061, i.e., fine-tuned to one with the precision of 0.006%.

- The ratio of 987654321 to 123456789 is equal to 8.000000073, i.e., eight with the precision of 10^{-8}. In this case, unlike in the previous two which are coincidences, there is a 'hidden' principle in number theory, responsible for the large amount of fine tuning. [42]

By the analogy with the last example, if we believe that a 'hidden' new principle in particle physics will be uncovered (and we believe it if we place bets on the future state of knowledge), running a competition between models by comparing their amount of fine tuning may seem to bring us closer to uncovering the principle. However, to adhere to this idea would be logically and methodologically incorrect, for the principles of Nature, both known and unknown, are unique — i.e., unstatistical — and independent of our will. Then, naturalness can only serve to satisfy a human psychological urge. We use it to please the senses by setting off the models in a beauty contest. Such a disappointing verdict for naturalness would indeed sound grim and gloomy, had it not been for its different, and a less nebulous, function.

5.2 Naturalness as heuristics

Karl Popper's falsification, which took much inspiration from the pretense to adequately describe the methodology of high-energy physics, relies on the assumption that physical experiment can rule out definitively certain predictions made within theoretical models. If this is the case, then the models, or at least such elements of these models that are directly responsible for the unfulfilled predictions, do not describe physical reality, and are false.

Popperian methodology depends critically on the possibility to interpret experimental data. If the findings are not conclusive, models cannot be falsified in the original sense of Popper's. Yet in particle physics of the last 25 years experimental findings have not been conclusive. While the power of particle accelerators grows and their exploratory capacity continues to be gradually augmented, no recent accelerator experiment has falsified a theoretical model, even if, in accordance with the falsification doctrine, the predicted phenomena had not been observed. This is chiefly because experiments at particle accelerators, as well as the gathered cosmological data, are so complex that one is unable to set up a unique correspondence between data and predictions made within theoretical models. We often ignore if we already possess a name or a theory for what we have observed. Unambiguous falsification of the models in particle physics is therefore impossible. At best, experimental findings suggest that certain predictions, while not completely ruled out, are rather difficult to sustain as open possibilities.

Departing from the original Popper's view, methodology of particle physics mutates thus into its probabilistic version. Complex experiments at the accelerators leave any model with a chance to die and a chance to survive, but never act as definitive model murderers. Notwithstanding, a model can still die: not because it was falsified, but merely for falling out of fashion.

The rise and fall of theories and models in contemporary particle physics is more a matter of a partly circumstantial history than subject to a rigorous epistemology. Influence of the sociological factors can be decisive, e.g., the choice at the leading universities of professors with a particular taste in physics, or the abrupt reversals between fashionable and worn-out lines of research. The argument from naturalness is a powerful instrument for influencing the development of particle physics, for, in virtue of having the form of a normal scientific argument, it can speak to the scientist. Indeed, arbitrariness of the measure of naturalness used for comparing different models is disguised. On the surface, one only encounters a presumably legitimate comparison of numbers, which does not bear any sign of the underlying problematic choice of the limiting range of parameters in the parameter space.

Those who are the first to fix the arbitrary convention of what is natural and what is not, exercise significant influence over those who will follow later. Wilson, Barbieri and Giudice did so. In particular, Barbieri and Giudice gave a mathematical definition of fine tuning, providing a definite form to what had only been a vague feeling of aesthetical unease. Ever since the 1990s, their work has been turned, albeit usually in the hands of others, into a powerful sociological instrument.

Imagine two models which theoretically explain away the big hierarchy problem, meanwhile no experimental measurements can be made to distinguish between them. The only possible competition between the models is based on purely mathematical criteria such as the numerical value of fine tuning. To know which model will win in the course of history, provided that experimentalists are unable to settle this question, one can only make guesses. And to make a plausible bet in this uncertain future-oriented competition, it may be helpful to use the heuristics of naturalness.

Now imagine that in the future the current argument from naturalness is sociologically overrun by something else. No matter what the modification will be, it is only likely that the argument accepted by the scientific community will mutate into another argument accepted by the scientific community. That fine tuning would be altogether proclaimed irrelevant or invalid, can hardly be envisaged. Influence of the naturalness heuristic initiated in the 1980s cannot be erased. Indeed, one such modification happened around 2000, when, without having previously been a scientific argument for model comparison, the argument from naturalness grew into presenting itself as such, and at the same time continuity was forcefully proclaimed with the original notion.

Trends in the model building in particle physics were formed by the naturalness-based heuristics, which is instrumental in dismissing "unnatural" theories and could yet lead to a "more complete model" explaining stability of the weak scale [3]. Physicists sometimes see clearly this mutation of the fine-tuning heuris-

tics. For example, Binétruy *et al.* warn that

> The [fine-tuning] approach should be treated as providing guidance
> and should not be used for conclusions such as "the heterotic string
> theory on an orbifold is 3.2σ better at fitting data than a Type I
> theory..." [14]

But even if such warnings are heard, and the direct judgment of the kind "one model is better than another" avoided, the sociological heuristics is still at work. One its manifestation is that working physicists will turn away from highly tuned models because their faith in them has been lost. This is connected with the Bayesian meaning of naturalness as "degree of confidence".
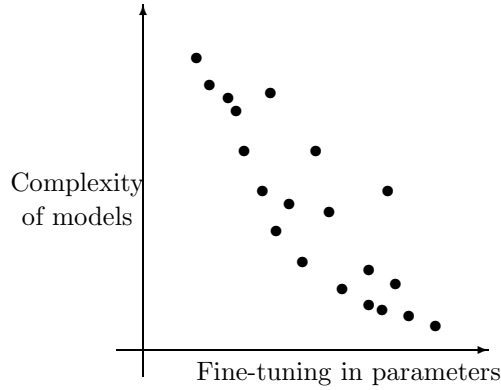

Figure 2: Schematic graph of fine tuning versus model complexity in the space of models beyond SM [24].

Another manifestation is that the heuristics of naturalness has so influenced model building that no simple model without significant fine tuning remains in the valid model space (Figure 2). Unnaturalness of simpler models led to the development of more complicated ones, which are allegedly less tuned. Even if at the end of the day such more complex models often turn out to be as tuned as simpler ones (e.g., see [55]), the sociological and historic influence due to the naturalness heuristics will have occurred before any such result can be established.

Research direction in particle physics moved away from the considerations of simplicity. This was hardly imaginable even a short while ago, when, e.g., Quine wrote that "simplicity, economy and naturalness... contribute to the molding of scientific theories generally" [52]. Quine's conventionalist view is intimately linked with the thesis of empirical underdetermination of natural science by observable events. It holds that the acceptance of a theory is a matter of choice guided by extra-scientific criteria, of which simplicity is one [51, 12].

Contrary to Quine, naturalness and simplicity are frequent rivals and pull physics in different directions. Dirac believed that in this case beauty has precedence over simplicity:

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> The research worker, in his efforts to express the laws of Nature in mathematical form, should strive mainly for mathematical beauty. He should still take simplicity into consideration in a subordinate way to beauty.... It often happens that the requirements of simplicity and beauty are the same, but when they clash the latter must take precedence [29].

Clashes happen more often these days, and the lack of simplicity can become dramatic. Complexity of some BSM models makes them less comprehensible, more difficult for doing calculations, and brings them closer to the status of a theory that we only believe, but do not know, to exist. Yet the beauty and elegance of simpler and easier to grasp models is accompanied by their low inverse fine-tuning probability. How will the rivalry between simplicity and naturalness end? Many a human researcher find it repulsive enough to look for less tuned, but also more complex theories which are harder to describe. Perhaps the difficulty of working with such models and extracting from them unambiguous predictions suggests a rapid end of the naturalness-based heuristic, as physicists will seek for dramatically different, but in a new way simpler solutions.

To this day, naturalness as heuristics has mainly served to support the claim for the inadequacy of the original Popper's falsificationism. If we are now concerned with the role of metaphysical and aesthetic arguments in science, in the future the greater influence of simplicity may yet prevail on the heuristics of naturalness. The latter would then be reduced to the purely circumstantial desire of certain scientists for a self-justification of their continuing work on the semi-dead physical models.

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